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PROGRESS IN APPLYING MAGNETO-OPTIC DETECTION METHODS TO FLAW IMAGING*

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Abstract: Magnetic garnet films $[(Tm,Bi)_3(Fe,Ga)_5O_{12}$ grown on $Gd_3Ga_5O_{12}$ by liquid phase epitaxy] have been used in our laboratory to image the magnetic fields associated with flaws in both ferrous and nonferrous materials. This progress is reviewed and prospects for additional applications and research are discussed.

Key words: Flaw detection; magnetic fields; magneto-optics

Introduction: In a recent series of publications (1-3) it was reported that direct flux-leakage imaging had been achieved using sensitive magnetic garnet films (4-6) as the detector of magnetic field anomalies associated with flaws in ferrous materials.

The purpose of this paper is to report the successful extension of this technology to flaw imaging in nonferrous conductors such as aluminum. Such an extension is nontrivial because the magnetic fields near flaws in good conductors with low magnetic permeability ($\mu \sim 1$) are generally very small at low current frequencies, whereas the magnetic fields near flaws in ferrous materials ($\mu \gg 1$) are relatively much larger owing to the fact that the magnetic flux is constrained (by the high μ) to stay inside these materials except near flaws where it "leaks" out and can be observed.

Generally in nonferrous conductors, the skin depth δ of currents is a good measure of the distance away from a surface breaking flaw (as measured parallel to the surface of the material) that the perturbed magnetic fields (due to time varying currents) will be appreciable. Thus in a good conductor where the B fields tend to be parallel to the surface, $B_{\parallel} \neq 0$ and $B_{\perp} = 0$ for distances greater than δ away from the flaw. However, when the distance from the flaw is δ or less, one finds that $B_{\perp} \neq 0$ and thus B can "leak" out of the flaw region much as it does in high μ ferrous conductors at low current frequencies.

Since uniaxial garnet films have an "easy" axis of magnetization (5) perpendicular to the garnet film plane (in our film it takes about 3 gauss to switch the film) - and a "hard" axis of magnetization parallel to the film plane (in our film it takes about 500 gauss to switch the film along the hard axis) it follows that for currents associated with a small δ (relative to flaw length) that the B field due to a flaw will alter the state of existing magnetization in the film if it is generally per-

pendicular to the surface of the conductor being examined. The general method of forming an image using garnet films was discussed at length in (1-3) and the reader is referred to those publications for further details.

Experimental Results: A typical arrangement for viewing the magnetic anomalies ($B_\perp$ fields) near flaws or artificial targets is illustrated in Fig. 1. This simple experimental arrangement makes it possible to view the state ["up" (on) or reflective state, "down" (off) or nonreflective state] of magnetization in the film near the flaw via the Faraday magneto-optic effect (6) thereby rendering the flaw visible. The first target inspected was an electro-discharge-machined (EDM) notch as illustrated in Fig. 1. The first experiment involved examining the open notch using direct current (actually half wave rectified current) supplied by a conventional magnetic particle type current source at 60 Hz.

Since the plate containing the EDM notch in our first experiment measured 10 inches by 10 inches by 1/8 inch and the peak current was about 850 A, the current density was approximately $\sigma \sim 109$ A/cm^2 throughout the entire plate thickness. The experiment was performed by laying a piece of Scotchlite reflector over the open EDM notch as shown in Fig. 1.   The garnet film was then switched to a uniform state of magnetization making it appear uniformly black (the "off" state) as viewed through an analyzer using a permanent magnet (or a current carrying coil surrounding the garnet film). The direct current source (supplying current to the plate) was then turned on and off momentarily and the garnet film examined in polarized light through the analyzer (no change in setting).

In Fig. 2, both the predicted and actual image for a garnet film that was initially switched to look black and which was then subjected to the current pulse are shown. Two things should be noted about this result. First, as expected, a low frequency (60 Hz) image does not resolve the EDM notch. The reason is that at 60 Hz the skin depth in aluminum is about 1 cm. This means that the currents will flow around the notch in such a way that current density gradients are significant out to distances δ from the open notch. Thus the notch will produce distortions in the current paths and normal magnetic fields $B_\perp$ up to 1 cm from the notch. That is a reasonable prediction in view of the low resolution image that was actually obtained. Clearly, to obtain a good eddy current image of this notch one will have to go to a frequency of say 30 KHz where $\delta \sim .02$ in $\sim .05$ cm which should produce a much more highly resolved image. The second thing to note about the result depicted in Fig. 2 is that it was obtained with a modest current density ($\sigma \sim 109$ A/cm^2). That is encouraging since it implies that if one can induce eddy currents with sufficiently large current densities at higher frequencies, one should expect to obtain a well-defined image of the notch.

To get an idea of what type of image one should expect from an open notch at 30 KHz, an open hole (1/4 inch diameter) was examined using a transformer source (7) and a 1/2 inch by 3 inch garnet strip placed between the contact electrodes (transformer secondary) as shown schematically in Fig. 3. The current was $I \sim 300$ A at 30 KHz. The result obtained is shown in Fig. 3 together with a schematic representation of the current path around the object. Note that once again the experiment was begun by switching the garnet film to a state where it appeared black (the "off" state) as viewed through the analyzer. The current source (transformer and power amplifier) were then momentarily turned on. The resultant image (Fig. 3) is very different from that expected for a low current frequency image (see also Fig. 3). At 30 KHz $\delta \sim .05$ cm and one sees immediately that the open hole is very well-defined as a bright area against a dark background. Note also that there is a small dark line (along the direction of the current path) that does not get switched by the alternating currents. This can be understood if the time varying magnetic fields $B(t)$ exactly cancel along this line for all times t, as illustrated in Fig. 4. Therefore,
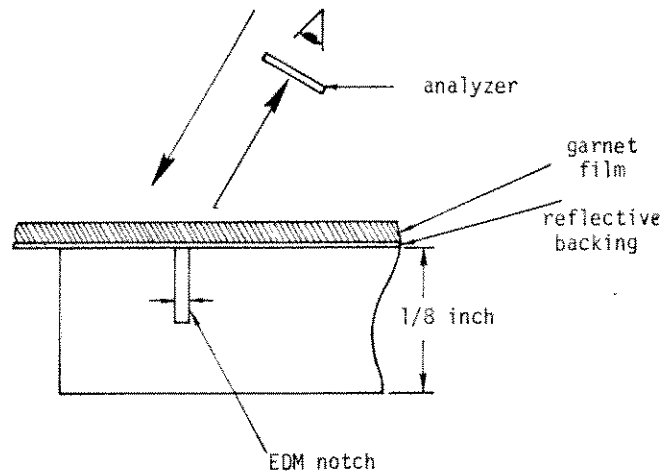
analyzer

garnet film

reflective backing

1/8 inch

EDM notch

Fig. 1. Typical arrangement for viewing magnetic anomalies due to eddy current distortions produced by a flaw.
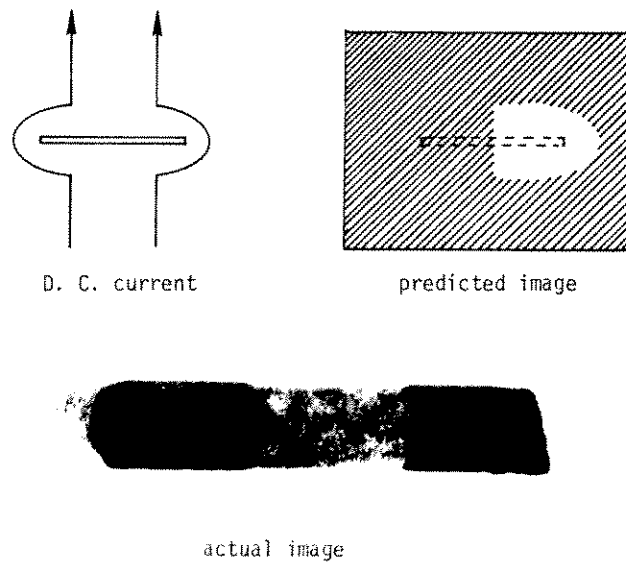

D. C. current

predicted image

actual image

Fig. 2. Predicted current paths and actual images for a notch type anomaly using a direct current source are illustrated.

electrode

garnet film

predicted
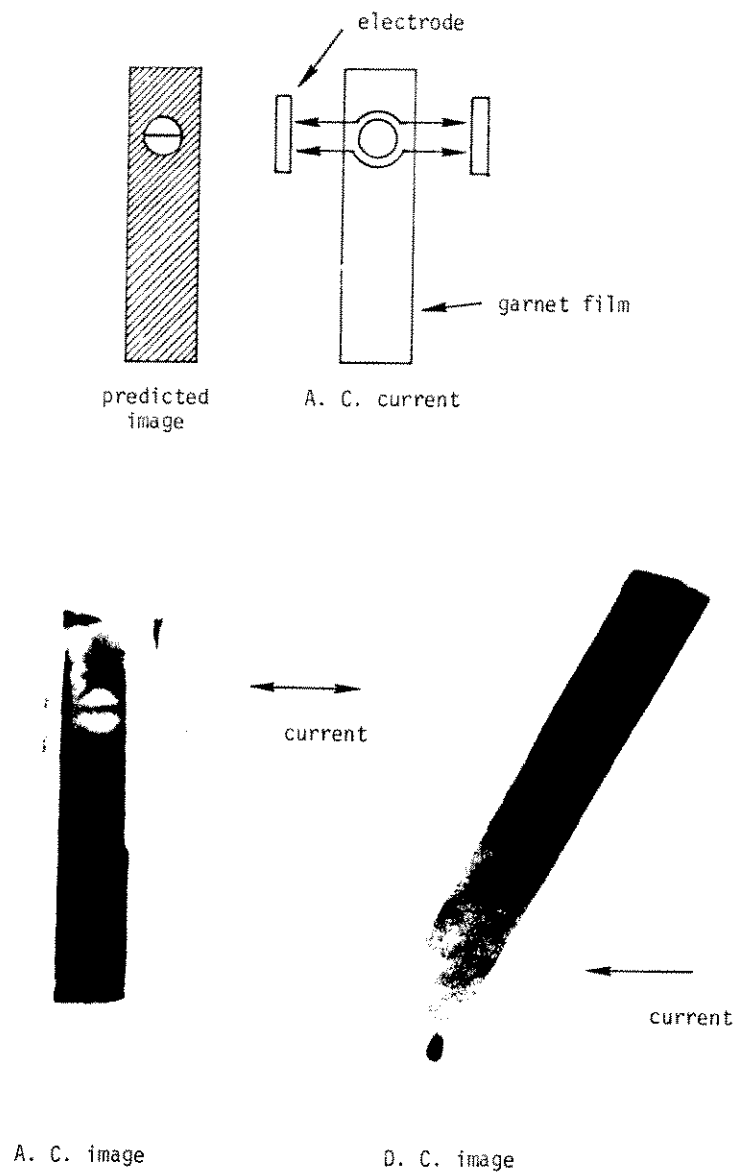image

A. C. current

current

current

A. C. image

D. C. image

Fig. 3. Current paths and actual images (A.C. and D.C.) produced for an open 1/4 inch diameter hole in aluminum (frequency 30 KHz).

currents

$B_\perp$ fields

+3 gauss

Bias

-3 gauss
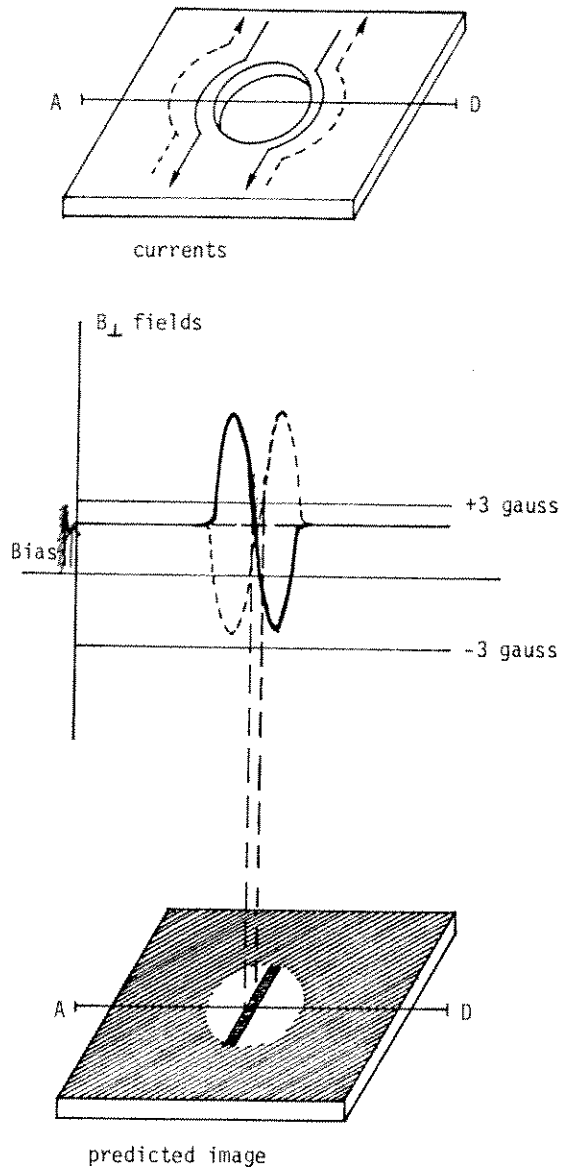
A ———— D

predicted image

Fig. 4.   Interpretation of the dark line in circular hole images at high frequencies
(30 KHz).   The garnet film is initially switched to look black (-3 gauss).
The alternating currents yield $0 < |B_\perp| < 3$ gauss along the "bar" and there-
fore cannot change this initial black or "off" state.   Note that during the
time the image was made a static reverse bias field was applied as shown.

if the film starts out in a given state of magnetization before the currents are turned on, it will remain in this state along this line.

It should be stressed that the sequence of steps for forming an image and the magnitude of the switching field (Bs) of the garnet film place certain constraints on the bias field [B(bias)] and the anomaly [$B_\perp$] which results from the applied currents. The imaging sequence is; 1) switch the garnet film to the "off" state (-3 gauss in this case), 2) reverse bias the garnet film with a uniform (if possible) static field where $|B(bias)| < |Bs| \sim 3$ gauss, and 3) induce currents in the specimen at 15-30 KHz, say, which produce time varying magnetic field anomalies not exceeding twice the switching field, namely $|B_\perp(max)| < 2|Bs|$. An examination of Fig. 4 shows that if these conditions are not met, no "permanent" image of the flaw can result. It is most encouraging (from a practical standpoint) that the induced currents need not (must not) be larger than some maximum value.

The results depicted in Fig. 3 represent a crucial test of the basic eddy-current imaging concept using garnet films. However, this target was a large open hole. What should a notch-like or crack-like target look like? A qualitative prediction is made in the series of sketches illustrated in Fig. 5.

To test this qualitative prediction a real fatigue crack emanating from an open 1/4 inch diameter rivet hole in aluminum was examined. Currents were induced in this specimen using the power amplifier-transformer combination (7) at 30 KHz. A garnet film with Scotchlite backing (similar to Fig. 1) was placed on the specimen. The results anticipated for an elongated hole (Fig. 5) lead one to predict an image something like that illustrated in Fig. 6 and, as illustrated in Fig. 6, a rather well-defined image of the type predicted was actually obtained.

It is instructive to examine the target used to make the image of Fig. 6 using a 60 Hz current source. The resultant image (not shown) was very similar to that illustrated in Fig. 2. Note again that at 60 Hz, the skin depth is $\delta \sim 1$ cm. This means that significant $B_\perp$ fields will be present at distances up to 1 cm away from the flaw boundaries. Of course, this also means that one cannot obtain a well-defined image of the flaw, as observed.

Recommendations and Conclusions: Owing to the cumbersome nature of contact-type current sources, noncontact methods (radiative coupling) of eddy current excitation are very desirable. One possible (though not very desirable) method of achieving radiative coupling is to employ a spark-like source. A spark gap and any linear section of conductor leading up to it constitutes a line source of electromagnetic radiation (see Fig. 7). The radiation tends to be linearly polarized along the direction of the current path and will therefore induce eddy currents as shown in Fig. 7. Clearly this type of source could serve as a noncontact source for producing eddy currents in a test specimen.

To obtain sufficiently large currents in a remote test plate, large currents must flow in the discharge circuit. A capacitor discharge circuit analogous to flash-lamp circuits and similar devices might well be appropriate. In order to put this basic idea to a preliminary test, a simple experiment was performed using an EDM notch and a critically damped flashlamp circuit of the type used in photography and laser pumping. The flashlamp was three inches long and 1/8 inch in diameter. When discharged, a current (approximately 100 A) passed through the arc and the lead wires. A magnetic field was thereby momentarily set up around the arc and these lead wires. However, since this particular lamp circuit was critically damped, the induced current (in the specimen containing the EDM notch located 5 cm from the flashlamp) is essentially a direct current pulse and would not be useful for forming an image.
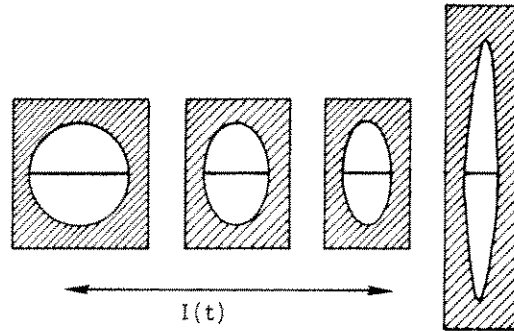
Fig. 5. In this figure a sequence of images predicted for open holes of ever
        increasing eccentricity at some fixed frequency 30 KHz are illustrated.
        One predicts that a long narrow open notch or crack-like target should
        appear as a long crack-like image as shown.

current path and   actual image
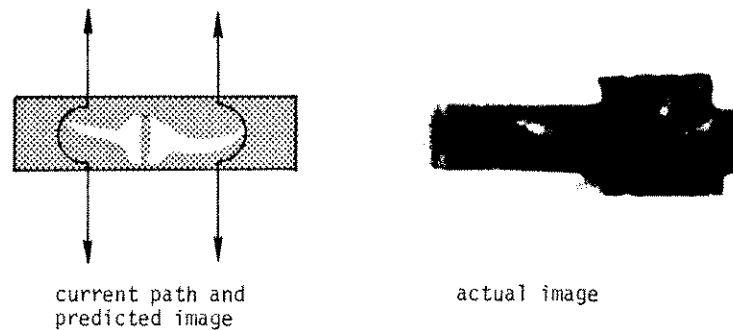predicted image

Fig. 6. Images produced of the crack in the aluminum dog bone specimen at 30 KHz
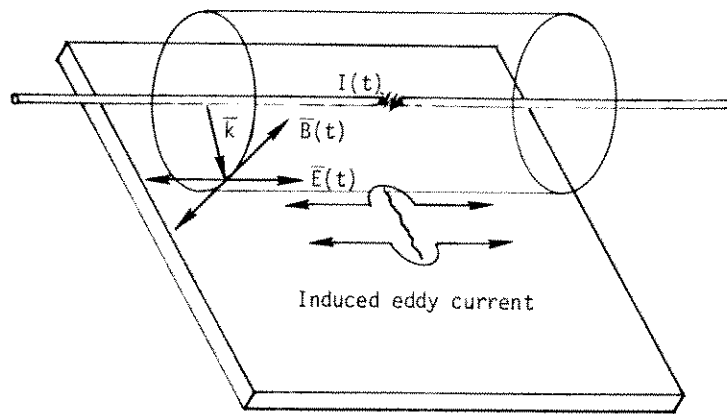   using a 1/2 inch wide, 3 inch long garnet film are illustrated.

Fig. 7. Radiation from a high current discharge tube in which an oscillating
        current I(t) flows during the discharge is schematically illustrated.

Nevertheless, one can obtain an order of magnitude feeling for the kinds of magnetic fields such a current source produces and also determine by direct experiments what effects these fields will have on the garnet films. A long, straight wire carrying a current $I\sim100$ A produces a circumferential B field at a radial distance $R\sim5$ cm from the wire of about $|B|\sim4\cdot10^{-4}$ Tesla or 4 gauss.

Clearly for $I\sim100$ A one can just begin to switch a 3 gauss garnet film at this distance. With several thousand amperes one could easily have magnetic fields measuring in hundreds of gauss. Such (B) fields would be associated with large currents flowing in a nearby test plate and could conceivably provide the desired radiatively coupled currents.

The flashlamp axis was aligned along a direction perpendicular to the axis of the EDM notch and parallel to the plane of the aluminum plate. This arrangement ensures that the eddy current paths in the plate will also be perpendicular to the long axis of the EDM notch as desired (see also Fig. 7). Although the EDM notch could not be resolved due to the large skin depth of this low frequency pulse, one could see that the EDM notch was nevertheless affecting the state of magnetization of the garnet film. The notch tip was surrounded on one end by a small bright spot while there was a boundary between dark and light on the other end. These results demonstrate the following:

1. The perturbing effect of the EDM notch can be seen through a thickness of aluminum.

2. The electromagnetic flashlamp fields from the currents in the flashlamp circuit are sufficient to induce currents in the test specimen of the correct order of magnitude.

3. Radiative coupling using higher frequency fields (smaller skin depths) should be able to resolve the notch through a thickness of aluminum.

These results suggest that it would be very worthwhile to pursue radiative coupling schemes further. Recently, in fact, a radiative coupling scheme involving a current carrying foil (skin depth $\gg$ foil thickness) below a 3 inch diameter garnet film and just above (and insulated from) a large area aluminum test specimen, was tried. Since this foil is close to the specimen the currents it induces are correspondingly larger than they would be if the foil had been placed at a greater distance from the specimen. Preliminary experiments at 30 KHz show that such a noncontact radiative foil source can be used to produce flaw images (the $B_\perp$ anomaly from the flaw penetrates both the current carrying foil and the garnet film) over a much larger aperture than was previously possible with contact current sources. Images produced with this arrangement of open holes and the fatigue crack are essentially the same as those produced using contact electrodes (see Fig. 3,6).

References:

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2. G. L. Fitzpatrick, "Imaging Near Surface Flaws in Ferromagnetic Material Using Magneto-Optic Detectors", Review of Progress in Quantitative Nondestructive Evaluation, edited by D. O. Thompson and D. E. Chimenti, Plenum Press, New York (1985), pp. 807-818.

3. G. L. Fitzpatrick, "Imaging Near-Surface Flaws in Ferromagnetic Materials Using Magneto-Optic Detectors", Eleventh World Conference on Nondestructive Testing,

ASNT (1985), pp. 186-191.

4. Magnetic garnet films $[(Tm,Bi)_3(Fe,Ga)_5O_{12}]$ were grown by one of us (J.K.M.) using liquid phase epitaxy on a garnet substrate $[(Gd)_3(Ga)_5O_{12}]$. The presence of Bismuth in these films, greatly increases the specific Faraday rotation.

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6. G. B. Scott and D. E. Locklinson, "Magneto-Optic Properties and Applications of Bismuth Substituted Iron Garnets", IEEE Transactions on Magnetics, MAG-12 (1976).

7. A transformer consisting of a 64 turn (#8 copper magnet wire) primary (with taps at 16 and 32 turns) wound on a low loss ferrite core (4 inches O.D.), and a single turn spool-type copper secondary which nearly surrounds the primary was constructed. The secondary was fitted with a variety of short (several inches) contact-type electrodes to deliver current to the specimens. Typical currents produced at the secondary (when shorted into the specimen) were in the range of 200-300 amperes depending on the length of the secondary conductors and the frequency of the input. A power amplifier was used to supply 4-5 amperes at 100 volts at frequencies up to about 30 KHz to the primary. When the secondary leads were shorted, the maximum measured current delivered was about 300 amperes at 30 KHz. Currents were measured using a flux-type current monitor surrounding one of the current carrying leads of the secondary.